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A cooperative multi-agent transportation management and route guidance system

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Abstract

Developing real-time approaches to manage roadway network congestion over time and space is a difficult problem. While many approaches to solving networking problems have been posed, the roadway routing problem is fundamentally different in that route choice behavior rests solely with the flow entities (drivers). The challenge is to find and implement solutions that achieve an efficient reallocation of network capacity over time and space without seriously violating any individual user's preferences for mode, routing, departure, and/or arrival time. This paper proposes a solution approach based on cooperative multi-agent-based principled negotiation between agents that represent network managers, information service providers, and drivers equipped with route guidance systems. It is demonstrated that the cooperative, multi-agent approach is a natural extension of the National ITS Architecture. Furthermore, the approach is highly scalable and adaptable to a variety of networks and user populations.

Keywords: Intelligent agents; Principled negotiation; Route guidance; Traffic management

1. Introduction

Traffic congestion is a serious problem in the United States and in metropolitan areas around the globe. Because of large costs and limited rights-of-way, it is impractical to rely on new roadway construction or widening of existing roadways to increase system capacity. Rather, the focus is on developing Intelligent Transportation Systems that are capable of better managing existing capacity and encouraging more efficient vehicle routing over time and space.

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The roadway routing problem can be described as follows. On the demand side, as time unfolds, there are people wishing to make trips across a multi-modal network. These travelers have origins, destinations, and implicit preferences for mode, departure time, arrival time, and route choice. In urban areas, there is a reasonable probability that demand will exceed supply (volume will exceed capacity) due to recurring and/or non-recurring congestion. It will become necessary to regulate the supply–demand interface by both adjusting supply-side control devices and encouraging reallocation of trips among modes, in time, and/or between facilities. The challenge is to find and implement solutions that achieve an efficient reallocation of network capacity over time and space without seriously violating any individual user's preferences for mode, routing, departure, and/or arrival time. The redistribution of trips among available modes and across time tend to favor better pre-trip decision making while the redistribution of trips between facilities tends to be a real-time decision making problem.

A representation for a typical urban transportation roadway system and its key components is shown in Fig. 1. The top portion of the picture depicts the *supply-side* management system hierarchy. This reflects a distributed, hierarchical system of virtual managers that work together in parallel to maintain quality of service across different sections of the roadway network. They are responsible for supply-side management functions such as collecting and storing data gathered from the network, adapting traffic signal and ramp meter timing plans, coordinating incident management, and disseminating traveler information through variable message signs and highway advisory radio. In a fully automated Advanced Transportation Management Systems, these managers are computers.

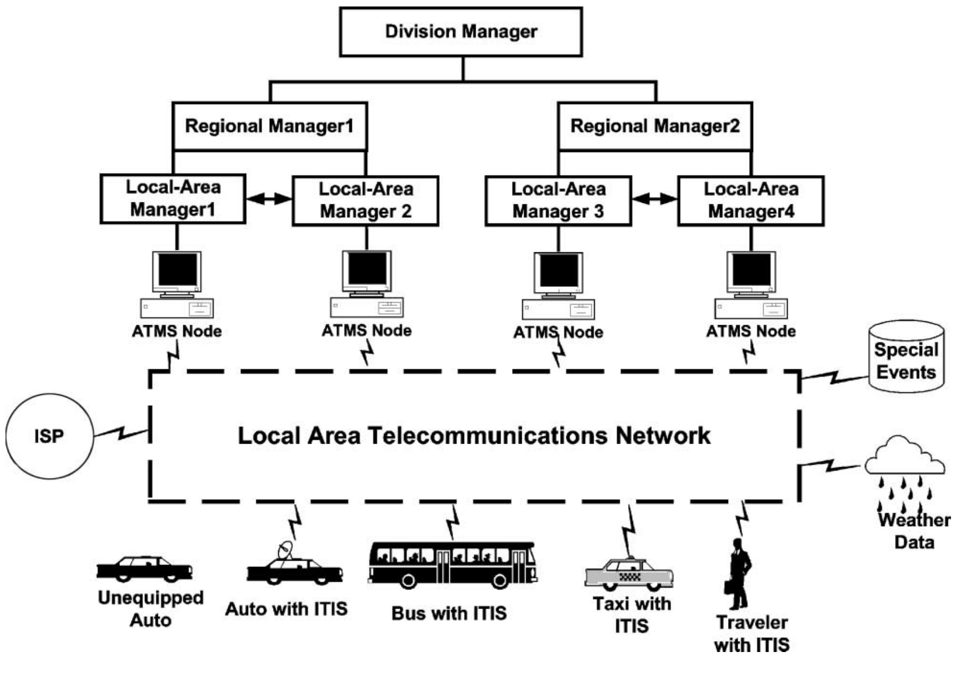

Fig. 1. Conceptualized distributed transportation network.

The lower half of the picture depicts the set of travelers and flow entities seeking to travel through the network. Users will be divided by mode as well as their telecommunication connectivity. Connected users are assumed to have Intelligent Traveler Information System (ITIS) capable of providing route guidance and/or traffic advisories both pre-trip and while en-route. [2] As shown in this Fig. 1, a transportation network can accommodate a diversity of participants.

An information service provider (ISP) is shown on the left side of the figure. ISPs collect, process, store, and disseminate transportation information to the network users. An ISP provides a general data warehousing function, collecting information from transportation system operators, and redistributing this information to other system operators in the region and other ISPs. The second role of an ISP is focused on delivery of traveler information to subscribers and the public at large. Information provided includes basic advisories, real-time traffic condition and transit schedule information, yellow pages information, ride matching information, and parking information. ISPs can also provide the capability to provide specific directions to travelers by receiving origin and destination requests from travelers, generating route plans, and returning the calculated plans to the users. In practice, there could be one or more ISPs that serve a roadway network.

The right side of the figure depicts *information sources*; a class of entities not directly tied to the supply managers or system users that are connected to the knowledge network to provide support information. Examples of information sources include weather stations and special event generators.

The National ITS Architecture (USDOT, 1999) defines a common communication infrastructure to enhance transportation management through better cooperation between network operators, managers, and travelers. The architecture defines the integration of 19 transportation subsystems through several modes of communications. Within this architecture the individual market package most closely related to the network as defined in Fig. 1 is ATIS6—*Integrated Transportation Management/Route Guidance*. This package, shown in Fig. 2, illustrates the fundamental subsystems, terminators, architecture flows, and equipment packages required. The market package in the ITS Architecture is defined as follows:

> *Integrated Transportation Management/Route Guidance*: This market package allows a traffic management center to continuously optimize the traffic control strategy based on near-real time information on intended routes for a proportion of the vehicles within their network while offering the user advanced route planning and guidance which is responsive to current conditions. It would utilize the individual and information service provider (ISP) route planning information to optimize signal timing while at the same time providing updated signal timing information to allow optimized route plans. The use of predictive link times for this market package are possible through utilizing the market package ATMS9—Traffic forecast and Demand Management (not shown)—at the traffic management center.

[2] ITIS is a term coined by Adler and Blue (1998) to describe next generation information devices that can both gather and process information as well as learn and represent user preferences and behavior. Intelligent traveler information systems are a requirement for the multi-agent model described within this paper.

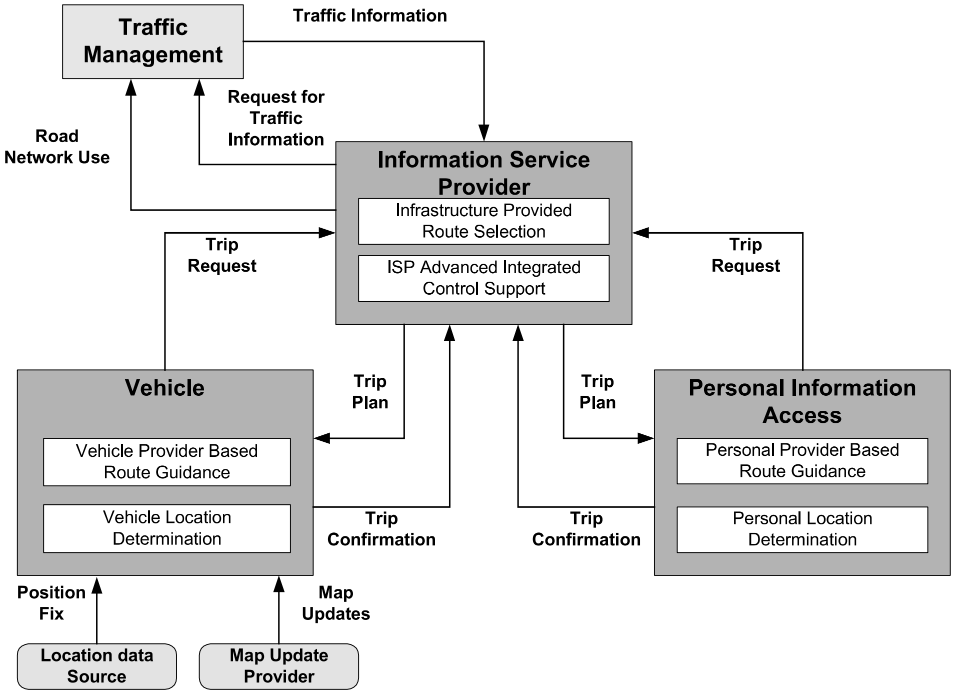

Fig. 2. Market Package ATIS6—Integrated Transportation Management/Route Guidance.

Within market package ATIS6, the ISP serves as a repository for traffic information. An ISP assumes the task of computing best routes for the individual subscribers. A driver would contact the ISP via in-vehicle routing and navigation system and issue a trip request. This request includes relevant details (e.g., destination and travel preferences) for the trip needed by the ISP to process (e.g., destination and travel objectives). For travelers not driving an auto, their link to an ISP can be through any wired or wireless communication device. Information flow between travelers and ISPs will occur both pre-trip as well as en-route if needed.

The advantages to adopting this quasi-centralized approach to route determination is that an ISP can take traffic information from the TMC and couple it with travelers' requests to create a trip plan. Travelers would benefit by receiving trip planning information suited to their needs. The network operators would benefit by receiving real-time information on roadway use.

There are several disadvantages to this framework. First, it is quite possible that travelers could come to distrust the ISP's routing suggestions. If the ISP suggests a trip plan that the traveler perceives does not address his set of travel objectives, the traveler is likely not to comply with the ISP's suggested trip plan. Second, traveler privacy is a concern, as some travelers may not want to give the ISP too much information about themselves. Third, there are travelers who are against the idea of paying a third party information provider. Many believe that the government collects data and that tax-paying citizens should gain this information free of charge.

The purpose of this paper is to describe the specifications of a next generation traffic management system that can address many of the shortcomings identified and be consistent with the National ITS Architecture. The Cooperative Multi-agent Transportation Management and Route

Guidance System (CMTMRGS), is structured around a three-tier multi-agent system (MAS) framework that fosters intra and inter-tier communication and cooperation through principled negotiation (PN). Network-wide control is achieved through coordination among highly distributed network managers (represented by supply-side agents). Traveler routing and scheduling is achieved through PN between agents representing ISPs and agents representing individual travelers. From a system-wide perspective, the negotiation process will encourage more efficient routing by fostering better usage of existing roadway capacity over time and space.

While the application of MAS for traffic management has been researched by many, this is the first paper that proposes the use of PN as way to directly account for individual user preferences. This approach has the potential to reduce many of the shortcomings associated with TMC and/or ISP supply-side traffic management systems.

The paper is organized as follows. Section 2 discusses the motivation for using a cooperative multi-agent approach to transportation management. The problem is defined and placed in the context of well-known network routing problems. This is followed by an introduction to MAS and PN. The conceptual design for the CMTMRGS is presented. The paper concludes with additional discussion on the problem, extensions to the model, and research needs.

2. Research motivation

Real-time multi-commodity flow routing problems can be found in many disciplines and there are several well-established techniques to handle a diversity of problem formulations. The motivation for the cooperative multi-agent based transportation management formulation proposed in this paper is the acknowledgement that the real-time roadway routing problem is substantially different from classical network routing problems. This section provides a brief review of network routing problem classes and illustrates the similarities and differences posed by the roadway routing problem.

To help describe the similarities and differences between classical network routing problems and the roadway routing problem, we have devised a taxonomy. This taxonomy, depicted in Fig. 3, suggests that all network routing problems can be classified based on two primary attributes, *responsibility*, and *communication*. *Responsibility* refers to who is given ultimate responsibility for generating and assigning routes. In supply-side driven networks, such as telecommunications, the network manager(s) will generate the routing assignments. In other networks, such as roadways, the entities themselves are responsible for selecting routes. *Communication* refers to the level of interaction between the supply (managers responsible for the network) and demand (entities to be moved) in the network. Networks may allow for no, one-way, or two-way communication.

2.1. Class I—supply-side routing systems

If the roadway transportation problem is strictly cast as a classic computer or telecommunications networking problem, a number of differences is immediately noticed. First, packets in these networks blindly go where they are routed; vehicles do not. The operator of the vehicle possesses a set of behaviors and preferences that may or may not be known to the supply-side of the roadway transportation system. Even if provided travel assistance from a TMC, drivers can

		RESPONSIBILITY	
COMMUNICATION		**Network-Assigned (Supply-Side)**	**Entity-Assigned (Demand-Side)**
	No or One-Way	**Class I** Telecommunications "On-Line" Problems	**Class III** Santa Fe Bar Roadway Networks
	Two-way	**Class II** Aircraft Routing	**Class IV** **CTMRGS**

Fig. 3. Classification of multi-commodity flow network problems.

choose not to comply. In essence, vehicles can be seen as "intelligent, non-compliant entities" that must be "reasoned" with and cannot be "pushed" around the roadway network. Second, vehicles en-route can be considered uncorrelated, whereas, packets are a part of a greater whole. Third, packets can be dropped while en-route, this is not possible for vehicles; they must complete trips. Because of these differences, proposed solutions to computer network congestion, while relevant, are not adequate for the roadway routing problem.

Another important distinction between the telecommunications routing problem and the roadway routing problem is the availability of excess capacity. In the telecommunications world, capacity is not a major issue. Very large delays in routing have been reported when traffic exceeds 25–30% of capacity. Telephone networks are designed such that typical utilization on any link is below 40% and redundancy is used to limit link volumes. On transportation networks, congestion is caused by overutilization (demand exceeds capacity). As described earlier, adding capacity is no longer a viable solution for the roadway congestion problem.

Although comparisons with "on-line" problems, such as bin-packing (Chang et al., 1993 for example) and on-line scheduling (Hochbaum and Shmoys, 1987), are possible, solution approaches for these problems are also not adequate for the roadway routing problem. On the surface, one may try to cast the roadway routing problem as a variation on the multi-dimensional bin-packing problem. In this model, vehicles are items to be packed, and bin capacity is defined by the set of roadways. The interesting twist is that the drivers of the vehicles have preferences as to where and when they are going, leading to constraints on which "bins" an "item" is willing to be packed in. Furthermore, vehicles can make diversion decisions while en-route; this would be akin to items making real-time bin switching decisions apart from the supply-side packing algorithm. This aspect fully complicates an already NP-hard problem, necessitating the development of new heuristics.

2.2. Class II—the aircraft routing problem

In many ways, the aircraft routing problem may be most similar to the roadway problem. Until recent years, aircraft scheduling and routing was coordinated unilaterally by air traffic control

centers with input from airlines. Traffic and weather data were collected by these control centers and operating conditions were imposed on pilots. Ground delay and en-route metering are techniques imposed by traffic controllers to ensure a high degree of safety. While en-route, aircraft are tracked by regional air traffic control systems. There is a transfer of oversight as aircraft cross-regional boundaries.

Today, within the aircraft-airspace control system, aircraft (pilots), airlines, and air traffic control units are stakeholders and all participate in the planning and real-time operations. There has been a trend toward "free flight"—providing pilots with opportunities to suggest routes that they feel will better meet the airlines' objectives (reduced travel time, fuel consumption,...) while not compromising safety. While each decision-making entity has its own set of objectives and exhibit different behavior, cooperation is needed to ensure that demand for travel can be met while maximizing safety and minimizing delays. For example, a pilot cannot unilaterally select a flight path as conflicts with other aircraft can ensue. Negotiating between parties is needed.

There have been several efforts to develop distributed intelligence and agent-based solutions for the air traffic management problem. Distributed planning for air traffic control is discussed by Finder and Lo (1998). Steeb et al. (1986, 1988) describe distributed problem solving for air fleet control. Stengel (1993) and Belkin and Stengel (1993) develop intelligent approaches for flight control.

Wangerman and Stengel (1996, 1998) have extensively explored the use of PN and MAS to improve the aircraft/airspace system (AAS). Based on a game-theoretic description of the AAS they developed an agent-based control model that relies on PN to achieve compromise solutions of mutual gain for both the airlines/pilots and the ground control system. In this model, distinct agents are developed for the supply (air traffic management) and demand (airline/aircraft) sides. Production rule systems are used to model the declarative functions of each agent. Options considered by each agent are evaluated through multi-attribute decision theory.

The AAS model provided the inspiration for the proposed approach to model the roadway routing problem with agent-based PN. However, the nature of the control greatly differs between air traffic management and roadway traffic management. The air traffic system is based on centralized control. Primary control for takeoff, routing, and landings is delegated to the air traffic control system. The airspace is divided into sectors, each managed by a team of controllers. Control across sectors is coordinated through hand-off procedures.

While there are similarities, there are some important distinctions between aircraft routing problems and roadway routing problems. In aircraft routing, centralized control is the norm, rather than the exception, while on roadway networks the opposite is true. Furthermore, compliance is not a problem in the air traffic management problem. Pilots provide near 100% compliance whereas for the roadway system, no such assumption can be made. In fact, non-compliance is seen as a major impediment to traffic management systems based around route guidance. This concern underscores the need for having a transportation system that is a tuned to driver needs and preferences. As such, in coordinating demand-side requests within the roadway problem, the supply-side must be extra cautious to foster cooperation from drivers.

2.3. Class III—demand-driven routing

The well-known Santa Fe Bar Problem (SFBP) (initially formulated by Arthur (1994)) and its extensions (such as considering cases of multiple bars, pricing, and the like) are Class III network

routing problems in which individuals are entirely responsible for travel decisions. The SFBP is defined as follows. Consider a local bar with capacity C offers entertainment and there are N people considering going to the bar on a given evening. It is known that when patronage exceeds C, the bar becomes too crowded for its customers to have a good time. The problem is for potential customers to decide if they want to go to the bar and at what time they should arrive. The SFBP has become a standard for studying network control and rational learning.

The SFBP can be readily compared to a roadway routing problems on a two-node two-route network (TNTRN). The TNTRN can be formulated as a non-cooperative game, akin to the SFBP with two bars, where the strategy of each driver is to determine the optimal departure time and route choice. The "payoff" for drivers is their travel time through the network that is computed as a function of volume on their selected route. The relationship between the SFBP and TNTRN problems is more evident when considering pricing effects. Greenwald et al. (1998) discuss the use of pricing to curb demand in the two-bar problem as a way to demonstrate the potential for using pricing to control quality of service in multi-media networks. The effects of congestion pricing to control demand on the TNTRN problem is well documented in the transportation economics literature (for example see Arnott et al., 1990a, b; Bernstein, 1993, and El Sanhouri and Bernstein, 1994).

Although the analogy between the SFBP and TNTRN is strong, it begins to breakdown when considering dynamic, multi-commodity flows across large transportation networks. Mathematical economics (see for example Varian, 1993) computational economics (see for example Pnueli et al., 1987 and Szymanski et al., 1985), and non-cooperative game theory (see Levy and Rosenschein, 1992 and Basar and Olsder, 1995 for example) can be used to provide different theoretical descriptions for the SFBP and other types of distributed user-based decision-making environments. However, the computational complexity of these models and the inability to realize these models precludes their use for on-line, real-time scenarios.

2.4. Class IV—distributed routing with two-way communication

Based on the discussion above, it can be seen that there are really no existing models or frameworks for Class IV systems. The real-time dynamic roadway routing problem on instrumented networks is unique in that communication between drivers and system managers is needed to promote optimal solutions. First, since transportation networks are dynamic and stochastic, real-time information is necessary to support effective route choice. Second, within ITS networks, the system managers are responsible for data collection and data storage. Although in-vehicle DRGS can aid with routing decisions, they are not capable of handling the large data needs and must rely on the knowledge network to gather needed information from the system. Last, since the challenge is to both attain efficient capacity allocation network-wide and satisfy each driver's routing needs and preferences there is value in cooperation between demand and supply-side entities. Feedback on vehicle location aids supply-side traffic control. Traffic advisory information supports demand-side pre-trip and en-route wayfinding.

Within the transportation network domain there has been research focused on distributed intelligence approaches to various aspects of the routing and network management problem. On the supply-side, much of the work has been performed in the context of developing dynamic traffic assignment (DTA) systems. Mahmassani et al. (1993a, 1993b) provide a thorough discussion of

the application of DTA and off-line simulation models for Advanced Transportation Management Systems. Ran and Boyce (1996) discuss DTA as it relates to managing ITS networks. Bottom et al. (1999) provide a thorough overview of generating route guidance with simulation techniques. For the most part DTA are supply-side driven models seeking optimal assignment of vehicles to the network. Changes in signal timing and dissemination of information by variable message signs are used for influencing routing patterns. Restrictive assumptions of driver behavior are used to develop closed form models.

3. Distributed artificial intelligence and multi-agent systems

Distributed artificial intelligence (DAI) is an approach to controlling large-scale systems by decomposition and distribution. Large systems are decomposed into a series of interconnected smaller subsystems, each responsible for controlling its domain and coordinating activities with surrounding subsystems. DAI techniques can create a more robust control environment through faster response, sharing of critical resources, and increased flexibility in adapting to changes in the system.

Agent oriented techniques are well suited for real-time DAI applications. The term 'agent' denotes a hardware or software-based computer implementation that supports a context of autonomous decision-making. Agents are not simply objects or actors, but also must autonomously attempt to reach goals and interact with other agents independent of simply solving the problem themselves. According to Wooldridge and Jennings (1995) agents are designed to support five categories of functionality:

Interactivity—capability to interact with other agents;
Proactive—take action based on goal-driven behavior;
Reactive—perceive changes in the system and respond in a timely manner;
Rationality—actions are made to enhance the potential for achieving (or satisficing) stated goals;
Mobility—move around an electronic network to collect data and interface with other agents.

The term MAS describes an agent-based application of DAI. Using concepts derived from the field of artificial life modeling, MAS are capable of replicating the emergent intelligence that arises through the interaction within a problem domain of several entities, each having differing goals and objectives. A solution is achieved within MAS by fostering interactivity to resolve problems that arise from cooperative and competing goals between cognitive agents.

Burmeister et al. (1997) suggest that MAS are appealing for conceptualizing and describing complex systems. They state that "the benefits of adopting an agent-based approach is the ability to reduce the complexity due to the concise and natural modeling of the problem domain, and enhanced robustness and adaptivity due to self-organization of the subsystems". There are three conditions under which agent technologies can significantly aid in the design and analysis of problem domains:

1. the problem domain is geographically distributed,
2. the subsystems exist in a dynamic environment, and
3. subsystems need to interact more flexibly.

Application domains for which distributed intelligence and/or agent-based systems have been studied include work on Internet management (Bivens et al., 1999a,b) and research by others on telecommunications networks (Hsiao and Lazar, 1988; Shenker, 1995; Korilis et al., 1995), and electronic commerce (Sandhom and Lesser, 1995), among others. Within systems involving heterogeneous agents, negotiation and/or cooperation can result in a more flexible and effective implementation (Lesser and Corkill, 1981).

Managing roadway networks is a problem domain that also satisfies these three conditions. Traffic management can be characterized as a highly distributed process involving the coordination of traffic control devices, signage, and sensors. Depending on the size and composition of a roadway network, decomposition can occur on several layers leading to a hierarchical, distributed management architecture. MAS are appealing for modeling transportation management. Agents can be assigned to model both individual control entities as well as regional control centers. Agents corresponding to entities in the same region are hosted together in the same agent community, so that they have a high-bandwidth, low latency communication among them. Vehicles may be modeled as mobile agents that move between regions and whose control is handed off from one agent community to another, akin to an air traffic control system.

Finder and Strapp (1992) present a distributed approach to optimized traffic signalization control. Iftar (1997) developed an intelligent control approach to decentralized routing and flow control. This model aims to achieve system optimality while ignoring drivers' routing preferences. As such, it is better suited for automated highway systems. Various solutions for adaptive management of networks and traffic management centers have been proposed (Cuena et al., 1995; Chang et al., 1995; Grasso et al., 1995; Molina et al., 1995, among others). Bromarius (1992), Burmeister et al. (1997), and Logi (1999) among others have studied the application of agent-based systems for supply-side control and optimization.

Li et al. (1996) suggest a "cooperative traffic scheduling and controlling system" based on a multi-agent framework. They suggest a three-level architecture of global, group, and individual entity planning and demonstrate how it could be used for control of traffic signals. Wide-area control and routing is not addressed. However, the difficulties in developing a wide-area control and routing model are acknowledged. In general, these models focus strictly on supply-side control issues and do not direct cooperation and coordination of drivers. As a result, while sensing and control will be enhanced, it is difficult to achieve area-wide improvements in routing.

For the most part, previous attempts to design distributed or MAS models for ATMS are rooted in the theory that a more flexible and robust approach to improving coordination of traffic management will significantly improve incident detection and response, traffic signal coordination, coordination between freeway and arterial subnetworks, and dissemination of traveler information via HAR and/or VMS. There is less emphasis on tackling the important issue of encouraging more efficient vehicle routing over time and space. This has been studied almost exclusively within the field of DTA.

4. Principled negotiation

PN was first proposed by Fisher and Ury (1983) in their best-known conflict resolution book, *Getting to Yes*. PN is a form of interest-based negotiation in which problems are stated in terms of

interests, not positions. The objective of PN is for both parties to reconcile their interests to obtain a mutually satisfactory solution. Parties seek options for mutual gain and apply objective criteria to judge the fairness of any proposed settlement.

Four basic components define PN:

1. Separating the participants from the problem.
2. Focusing on interests, not positions.
3. Generating a variety of possibilities for mutual gain before deciding what to do.
4. Insisting that the result be based on some objective criteria.

Lesser and Corkill (1981) showed that within MAS involving heterogeneous agents, negotiation and/or cooperation can result in a more flexible and effective implementation. In this light, PN is well suitable to model interactions between agents within a MAS. Negotiating toward a mutually acceptable resolution is enhanced when the two agents generate a single set of objective criteria to assess alternative options. An alternative scenario is for each agent to have their own set of objectives but agree to share these objectives with the opposing agent before negotiations take place. In either case, having perfect knowledge of an agent's set of criteria will make an agent's negotiating behavior more transparent. When both agents understand each other's current and desired negotiating positions, coming to a mutually acceptable solution is realized in a faster, more direct manner.

Within MAS, the PN process begins when one agent formulates an option and initiates contact with a second agent. Within this initial contact, the parties discuss the use of objective criteria, effectively agreeing to share a common set of mutually beneficial objectives and/or inform each other of their respective objectives. The second agent receives the option and assesses it against his set of objective criteria. One of three outcomes is possible: the second agent may reject the option, accept the option, or propose a counter offer. If the latter results, the roles reverse and the second agent submits an alternative option. The first agent assumes the position to assess and respond. This "give and take" negotiation continues until the agents come to a mutually agreeable solution.

While the concept of PN is relatively simple, the process is very robust and can be applied to a variety of scenarios and agents. A PN-based MAS requires defining the behavior of each agent and developing a set of protocols that define the negotiation process. Since agents reveal decision-making criteria to each other, differences between agents with regard to how proposals are generated and assessed can yield a variety of results. For example, suppose that agents adopt utility-based behavior. Variations will arise when some adopt a utility maximization approach while others seek to satisfice utility. Utility maximization lends itself to compensatory, non-compensatory, and hybrid strategies.

4.1. Applying principled negotiation to traffic management

Drivers and system operators have different objectives that each strives to satisfy. System operators seek to optimize overall system-wide assignment. Drivers seek trip itineraries whose performance will satisfy their individual travel preferences subject to prevailing network conditions. They also want their trip performance to be equivalent to others who are making similar trips through the network. This can be interpreted as the need to optimize perceived "quality of

service'' for each driver. Global solutions to the roadway routing problem must therefore be acceptable on two levels—satisfying individual drivers and the network as a whole.

Traditionally, the success of ITS technologies, such as route guidance systems, is measured by improvements in system performance as a function of market penetration and levels of user compliance. Too often, the issue of individual driver quality of service is overlooked or downplayed as supply-side traffic management systems strive to optimize network performance. Traffic assignment approaches are based on assumptions regarding driver preferences and system-wide objectives. While ''equilibrium'' solutions often satisfy supply-side objectives, there is little evidence that expectations of individual drivers are met.

Intricate DTA models, especially those that incorporate multiple user classes and multiple criteria path evaluation, aim to effectively trade-off user equilibrium (UE) and system optimal (SO) solutions. However, solutions achieved through these models have only theoretical validity. There are no practical means for implementing such multiple user class solutions. The system has no way of forcing vehicles to follow the resulting path assignments as even the best designed route guidance systems can only encourage drivers to take certain paths. Furthermore, there is no guarantee that all drivers will find the solution personally appealing. For many, the assumed multiple criteria path evaluation will not match their personal preferences and these drivers may not realize any improvement in quality of service. As a result, driver compliance is acknowledged to be a primary impediment to realizing any ''optimal'' assignment derived from DTA modeling.

Approaches to traffic management that will be perceived by drivers as increasing quality of service and resulting in increased compliance will require more active involvement of drivers themselves. Directly involving drivers in the assignment process can help achieve this goal. A traffic management system that is based around PN has the potential to overcome the problems of compliance and encouraging drivers to work with the system operators to generate assignments that are mutually beneficial.

In PN applications, the people are separated from the problem by using the goals rather than their positions to find the solution. In traffic management, this translates to combining the goals of individual drivers and the system operators leading to a cooperative aggregated goal that meets mutual needs. The PN traffic management model uses goals rather than positions to achieve an efficient reallocation of network capacity over time and space without seriously violating any individual user's preferences for mode, routing, departure, and/or arrival time. The goal is to achieve a more efficient metering of scarce roadway capacity by steering drivers toward paths that will satisfy their individual needs while also improving overall network performance. A good solution derived from PN will result in drivers being satisfied that their needs and preferences were achieved by their resultant trip itinerary and the TMC being satisfied with improved system-wide performance.

5. Conceptual design of the CMTMRGS

PN is the cornerstone of the proposed CMTMRGS, an architecture designed to facilitate communication and efficiently and amicably generate trip assignment agreements between supply and demand-side agents. While the conceptualization of the proposed CMTRGS has been influenced by work in the transportation domain, the focus on adopting a cooperative MAS

approach is derived from research on agent-based systems that have been successfully developed for class I–III routing problems described earlier.

Traditional approaches to modeling roadway networks assume that both network operators and drivers are self-interested. As a result, most planning models treat the problem as a non-cooperative game and seek an equilibrium solution in which optimal path assignments are sought. In the proposed CMTMRGS, we seek to treat drivers and network operators as cooperative entities. While they are interested in satisfying their own objectives, each needs the help of the other in pursuit of this outcome. Drivers are ultimately responsible for making travel choices. However, the process of choosing a best path over time and space is greatly enhanced by acquiring information collected by the system. Network operators have the capability to adjust traffic control devices and information displays. System prediction and estimation are enhanced when more information on vehicle demand and routing is known.

Placing one or more ISPs between the driver and the system operators is necessary for protecting driver privacy, reducing the burden on system operators to package information, and limiting potential liability of the system. Individual privacy has emerged as a central theme for increasing the public's willingness to adopt ITS technology. ISPs presumably will have more acceptable privacy policies for their clients than a government-run TMC. Furthermore, privatizing the packaging of the information and the negotiation of trip itineraries should result in better service and attentiveness to driver needs as ISPs compete for users. It is likely that the public would be more responsive toward the privatization of this route guidance service. In this model, ISPs are the primary point of contact for travelers seeking information.

Fig. 4 illustrates the CMTMRGS for roadway routing. It is a pure extension of the ITS Architecture market package ATIS6 that accounts for automating communication between drivers and ISP agents and between ISP agents and agents for supply-side network managers. The CMTMRGS extends the ITS National Architecture Market Package ATIS6 by adding a layer of distributed intelligence that is comprised of actors and protocols. The actors are agents that represent travelers, ISPs, and network managers. These actors will represent their owners and conduct all of the interactions described in ATIS6. The protocols are rules that govern the interaction of the agents. In the CMTMRGS principled negotiation provides a framework to model interactions between driver and ISP agents. It is proposed that if travelers and ISPs pursue a collaborative, problem-solving approach to negotiate trip planning, better results will be realized on both sides. Travelers will be able to follow a trip itinerary that better meets their travel objectives. From the systems perspective, a more optimal assignment will be achieved and the risk of non-compliance will be mitigated.

The modeling of this interaction between supply (ISP) and demand-side (driver) agents is quite different from many traditional multi-agent systems because the supply-side agents ultimately do not have direct control over travelers. In fact, supply-side must make every effort possible to accommodate system users' requests to expedite the routing of travelers and ensure future participation of demand-side agents. As a result, different techniques must be developed to model this negotiation process which will lead to a new paradigm for distributed agent-based control—where a network of supervisory agents has only limited degree of influence over rational agents (i.e. travelers).

A major component of the CMTMRGS is the telecommunications system that supports the data collection and negotiation process across the system components. Telecommunications

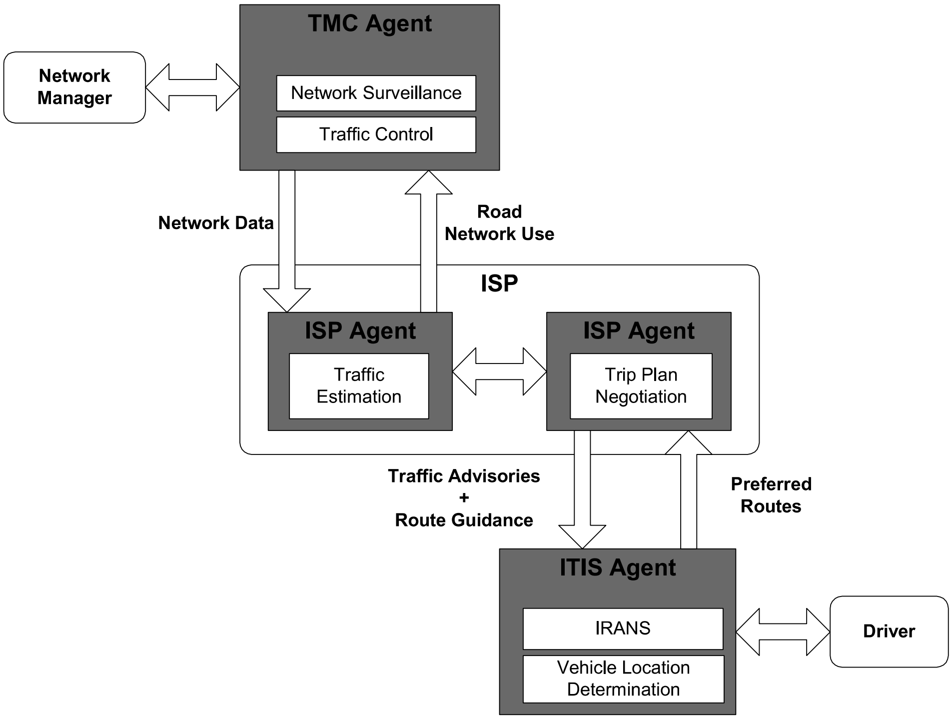

Fig. 4. Conceptual view of CMTMRGS.

infrastructure will include hardware and software issues, as well the protocols to dictate how individual entities transfer information to and from the network and communicate with other entities. The infrastructure must support the communication needs for the large number of entities while maintaining security, privacy, and connectivity. Since the purpose of this paper is to introduce the PN approach for increasing the efficiency of routing and scheduling, this section will focus exclusively on the primary agents and the negotiation process. Issues regarding telecommunications, although important, will be addressed in subsequent papers.

6. Agent-based PN between drivers and information service providers

Based on the notion of an ITIS proposed by Adler and Blue (1998), it is assumed that agents that represent driver needs and preferences are coupled to an intelligent in-vehicle telematics device. In theory, this model can be extended to cover a variety of travelers and linked to a variety of telematics including personal computers, cellular telephones, or PDAs. For routing and navigational purposes there are five primary tasks to be performed by the ITIS: (1) learning driver preferences, (2) collecting traffic advisories, (3) finding best paths to the destination, and (4) negotiating best paths with the ISP, and (5) providing navigational assistance to the driver. ITIS agents will need to be collaborative and capable of learning. They must accurately represent the needs, preferences, and attitudes of the user. They devise trip plans by assimilating traffic information and applying network path search routines. The resulting trip plan is used by the ITIS to

provide drivers with direct navigational instructions if desired. The description of these latter tasks is the focus of this section.

It is also critical that these agents must be mobile, across both the communications network and physical network. If a driver's agent-based system communicates solely with an ISP, there may be less emphasis on mobility across the communications network. However, if interfacing with the ISP is only one activity of many—i.e., these agents will poll the communications network to acquire information, then the agents must be mobile across the communications network. Physical mobility is an important design consideration of the CMTMRGS. As travelers and their devices move around the transportation network, they must be able to maintain communication with the CMTMRGS and adapt their behavior to changes in the network over time and space.

The ISP is a conduit between the system operators and the drivers. The ISP enters into a cooperative agreement with the system operators. The ISP receives traffic data and traveler information from the network managers and in return, provides the network managers with information on current and anticipated roadway use gathered from its driver base. The relationship between the ISP and the drivers is less well defined. Drivers rely on the ISP for providing traffic advisories and seek to negotiate trip plans. However, since the ISP has a cooperative arrangement with the system, and the system-side traffic management objectives may differ from those of the individual driver, there is always an element of distrust among drivers. The functionality of ITIS and ISP agents are summarized in Table 1.

Table 1
Summary of ITIS and ISP agent functionality

	ITIS agent	ISP agent
Objectives	*Pre-trip*: Schedule an optimal trip plan	Support system operator to achieve better network performance
	En-route: Monitor network performance and, if necessary, adjust trip plan to satisfy travel objectives of the driver	Maintain quality of service among driver subscribers
Interactive	Communications with driver through telematics	Communicate with supply-side agents
	Communication and negotiation with ISP-agents	Communication and negotiation with driver-agents
Proactive	Plan travel goals and objectives	
	Estimate routing preferences of the driver	Data processing and synthesis
	Network analysis and path processing	Path evaluation
	Wayfinding and navigation	
Reactive	Adapt route guidance in response to updated traffic advisories	Respond to demand-side proposals
	Respond to ISP-agent proposals	Inform supply-side agents of changes in roadway use
Rationality	Synthesize information into knowledge	Synthesize data into information
	Consistent decision making	Convert information into knowledge
Mobility	Move through virtual network to collect data and interface with network operators and ISP	Interact with all supply-side agents within domain

Summary:	ITIS Agent seeks traffic advisory information from the ISP.
Flow of Events:	(1) The ITIS agent initiates a request for traffic advisories from the ISP Agent (2) The ITIS provides a basic set if trip parameters (e.g., destination, departure time, trip purpose) (3) ISP Agent provides relevant traffic advisories (4) The ITIS agent terminates the communication.
Exception Flow:	For subscriber-based ISPs, the flow of traffic advisories may occur in "push" (automated) mode rather than "pull" (requested) mode.
Assumptions:	ITIS Agent infers that a trip is to be made and seeks specific information
Preconditions:	None
Postconditions:	ITIS has the most recent set of traffic advisories and other information on the network.

Fig. 5. Request for traffic advisory use case.

There are two primary interactions between ITIS and ISP agents.

1. Passing of traffic advisories between ISP agents and ITIS agents.
2. Negotiating best paths based on mutual gain.

Figs. 5 and 6 depict use cases for these two tasks. Use cases specify a sequence of actions that is performed by a system and yields observable results of value to a particular actor in the system (Jacobson et al., 1999). [3] They are useful for describing the behavior of a system and its components.

Fig. 5 depicts the use case for passing traffic advisories from the ISP agent to the driver agent. This transaction of traveler information from ISP agent to driver agent can occur in two ways: "pull" or "push". In the "pull" scenario, driver agents formally requesting specific data from the ISP agent and "pulls" it down. Alternatively, in a "push" scenario the ISP agent constantly passes information to the driver agent who receives and processes the information. A "push" scenario is typical of a situation where a driver subscribes to an ISP.

The PN process applied to pre-trip route selection is illustrated in Fig. 6. To guide the PN process, the driver agent and the ISP agent try to agree on a set of objective criteria that will be

[3] A use case is a central component within the Unified Software Development Process. Formal nomenclature for use cases are defined within the Unified Modeling Language (UML), a graphical language to specify and document the artifacts of a software intensive system (see Booch et al., 1999 for an overview of UML).

Summary:	Negotiation between the driver's ITIS Agent and the ISPs Route Guidance Agent to identify the best trip plan for the driver.
Flow of Events:	(1)The ITIS agent initiates a request for a best route with the ISP Agent
	(2) The ITIS agent and ISP Agent agree on a set of objective criteria to guide the negotiation process
	(3) The ITIS agent determines a set of best trip plans based on the driver's destination, trip purpose, and routing preferences. A limited number of non-dominated trip plans are proposed.
	(4) The ISP Agent considers the request and can accept the proposal as submitted or make a counter proposal of mutual gain
	(5) The ITIS agent can accept or reject the counter proposal.
Exception Flow:	If the proposed route does not pass through critical links in the network or will occur in off-peak times, the ISP Agent can approve the request without negotiation.
Assumptions:	Both the ITIS and ISP agents accede to the principled negotiation protocols
Preconditions:	The ITIS agent is registered with the ISP
Postconditions:	A best route for the driver has been determined

Fig. 6. Pre-trip route choice use case.

used to evaluate trip plan options. If both sides can agree on the set of objectives, then it is more likely that a mutually beneficial solution can be reached. Furthermore, the negotiating process will be more predictable if each agent formulates options to satisfy this set of objective criteria. If formal agreement cannot be reached, each side will reveal their set of criteria. This provides the opportunity to propose and evaluate options for mutual gain.

During pre-trip planning, the PN process is initiated by the driver agent. Based on the driver's preferences and any traffic advisory information collected, the driver agent will compute the set of "most preferred" trip plans. Each trip plan includes a preferred route and departure time. This set, along with some indication of preference, is forwarded to the ISP agent for consideration. The ISP agent considers the traffic data and congestion prediction provided by the network agents and selects the trip plan that maximizes mutual gain. This option is returned to the driver agent who can accept or reject this proposal. If the negotiation proceeds in an honest manner and the driver agent is indifferent between the set of plans proposed to the agent, then the plan selected by the ISP agent is accepted. If the sides could not agree on a set of objective criteria, the driver agent may seek to renegotiate. Negotiations regarding en-route path switching would be handled in a similar manner, except that the trip plan will consist of an updated route. This pre-trip process flow is illustrated in Fig. 7.

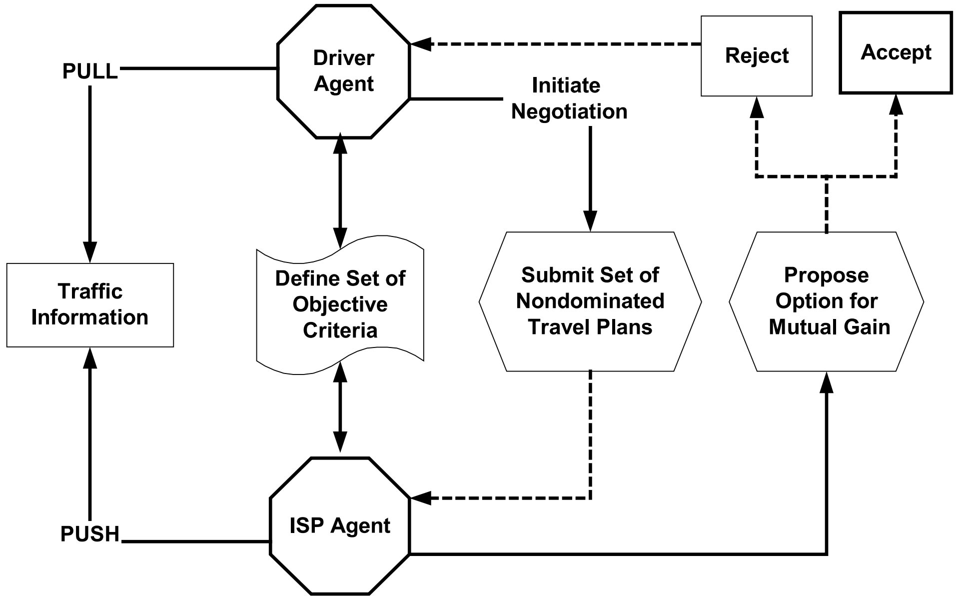

Fig. 7. Pre-trip PN process flow.

6.1. Extended vision of the CMTMRGS concept to the supply-side

The demand-side framework may be extended to the supply side. In this case, the ISP would develop and employ DTA algorithms to advance the needs of its clients. The ISP would receive real-time data from the TMC as part of a partnership with the TMC. The ISP DTA would employ whatever variants of its UE strategies to advance its clients through the network (e.g., multiple-objective routing) to get a larger market share from more satisfied clients. The ISP is envisioned as entirely client oriented and is somewhat in competition with the TMC's more SO worldview.

Routing information exchange between the ISP and TMC would assist the TMC's DTA to include the routings of the ISP and improve the capability of the ISP's DTA routines to find gaps for its clients to optimize their flows. This results in TMC-based SO and ISP-based UE to trading off one another. The smaller ISP client population gets better, personalized, in-vehicle routings. The larger TMC population receives routings by variable message signs and highway advisory radio that guide the system with an awareness of the ISP client routings.

Through simulation, the CMTMRGS could be analyzed to play out these competing strategies and estimate travel time savings for the ISP clients and the TMC-informed drivers. Without this coordination, and with only present-day, ad hoc judgements, ISPs and TMCs are blindly competing, likely to the disadvantage of both and generally rather suboptimally. Thus, the ISP–TMC cooperative data sharing could approximate multi-objective (SO and UE) network flow optimality. If there were multiple ISPs running DTA algorithms, the TMC's DTA would assure that the competing ISP routings would not be excessively conflicting. This scenario resembles the air traffic control problem where ISPs are like competing airlines and the regional TMCs are like the airport controllers.

7. Discussion and conclusions

This paper presented a conceptual model for CMTMRGS. The approach seeks to achieve a more optimal vehicle routing and scheduling by fostering interaction and cooperation between network operators and drivers. A distributed artificial intelligent approach based on mutual information exchange and PN between agents representing network managers, ISPs, and drivers is proposed. The central aspect of the proposed CMTMRGS is the PN process by which agents representing demand-side drivers communicate with agents that represent supply-side ISP and/or network managers.

The modeling of this interaction between supply and demand-side agents is quite different from many traditional MAS because the supply-side agents ultimately do not have direct control over travelers. In fact, supply-side must make every effort possible to accommodate system users' requests to expedite the routing of travelers and ensure future participation of demand-side agents. As a result, different techniques must be developed to model this negotiation process which will lead to a new paradigm for distributed agent-based control—where a network of supervisory agents has only limited degree of influence over rational agents (i.e. travelers).

This cooperative approach to traffic management is attractive on several levels. First, from a purely ITS perspective, the CMTMRGS is naturally consistent with the National ITS Architecture and provides a robust, scalable model for handling different configurations of system operators, ISPs, and drivers. From a driver perspective, the proposed CMTMRGS is appealing because it enables drivers to maintain control over routing. The use of PN between driver and ISP agents should support solutions that stress mutual gain. ISPs benefit from improved customer support and the opportunity to grow their subscriber base. From the network management perspective, the approach is appealing as real-time information on route choice and trip planning can be provided by the ISPs.

The vision for a CMTMRGS is certainly within reach. Recent advances in technology have resulted in strong market growth for in-vehicle systems that can support the integration of wireless voice and data systems. As these systems become more powerful and intelligent they will provide opportunities for drivers to store personal preference and receive personalized information "on demand". Currently several automobile manufacturers offer in-vehicles systems capable of interfacing with an ISP for safety and convenience services. Work is continuing at several research and development sites to create the next generation intelligent in-vehicle system. For example, Rogers and his colleagues at the DaimlerChrysler Research and Technology Center (Rogers et al., 1997, 1999; Rogers, 1998; Wilson and Rogers, 1998; Rogers and Fiechter, 1999) have been working on the personalization of the automotive information environment. They have created an *Adaptive Route Advisor* that resides within the in-vehicle system and uses agent-based techniques to lean driver preferences and predict a driver's preferred route for a given trip.

Over the next few years there will be a rapid expansion of the services provided by in-vehicle telematics, including: dynamic route guidance with automatic congestion avoidance, information and reservation services available from the car, reference to interesting points along the journey and even remote diagnosis of vehicles with dealers linked directly to cars. It is expected that the number of telematics subscribers in the United States will quadruple this year to 820,000 and surpass 11 million in 2004. Revenue from telematics is projected to climb from $40 million in 1999 to more than $1.7 billion in 2004.

Further research is needed to develop and test a working prototype of the CMTMRGS. There are three phases of work planned. The first phase focuses on the formal development of the driver-side and ISP agent architecture is being undertaken. Several models to represent driver and ISP behavior are being considered. In parallel, the formal protocols of the PN model will be further developed. In the second phase, the behavioral models will be integrated with the PN process and the negotiation process will be emulated. High-speed dynamic SO and UE algorithms would be adapted to determine the network arcs and paths that are most and least sensitive to loading by the ISP clients. MAS research needs to experimentally evaluate sensitivities of dynamic SO and UE assignments to compromise, determine allowable compromise levels, develop the arc tradeoff approach, and further modify the high-speed dynamic SO and UE algorithms for fast processing in this environment. The third phase is to implement a prototype CMTMRGS within a network simulation such as CORSIM. This will facilitate in-depth analysis of the PN approach and support studies to compare the performance of the CMTMRGS to various traffic assignment models. Congestion pricing and ISP pricing are additional areas of interest that will be studied.

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